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Incorporating the SSGN Firing Unit in the TOMAHAWK Missile Phase 1 Predesignation Heuristic

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Students and faculty in the Operations Research Department at the Naval Postgraduate School and researchers at the Naval Surface Warfare Center in Dahlgren, Virginia, have been developing an automated decision support tool for the Navy to optimally allocate to firing units tasks requiring Tomahawk Land Attack Missiles (TLAMs). A new type of TLAM firing unit, the nuclear-powered cruise-missile submarine (SSGN), will soon be operational. An SSGN will be able to carry a maximum of 154 TLAMs. This report describes how to incorporate the SSGN into the existing TLAM allocation decision support algorithm.

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ABSTRACT

Researchers at the Naval Postgraduate School and Naval Surface Warfare Center in Dahlgren, Virginia, have been developing an automated decision-support tool for the Navy to optimally allocate to firing units tasks requiring Tomahawk Land Attack Missiles (TLAMs). A new type of TLAM firing unit, the nuclear-powered cruise-missile submarine (SSGN), capable of carrying 154 TLAMs, will soon be operational. We consider how to adjust the data structures and model of the existing TLAM allocation decision-support algorithm to incorporate the SSGN, and find that only minor modifications are necessary. Furthermore, based on interviews with submarine officers, we validate certain SSGN operational constraints and discard irrelevant ones. Specifically, the algorithm must account for constraints on the maximum number of missiles that can concurrently be powered up, the minimum amount of time required to open and close a hatch from which a Tomahawk missile is fired, and the minimum amount of time required between missile launches.

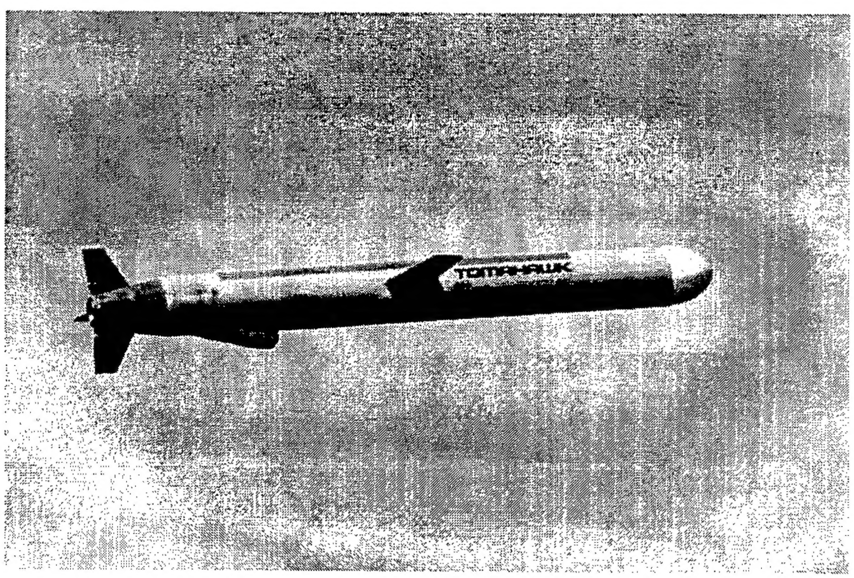

Figure 1 [Federation of American Scientists, 2002a]. A Tomahawk cruise missile, like the one pictured above, can be launched from surface ships and submarines. Allocating tasks to missiles is complicated by missile variants and firing unit limitations.

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The authors wish to thank Dr. Charles Fennemore and Mr. Robert Taft of Naval Surface Warfare Center, Dahlgren Division for their support and contributions to this TLAM predesignation research. We also wish to thank the officers, non-commissioned officers and sailors from Trident submarines at Submarine Base Bangor, Washington, for their invaluable feedback on, and support of, this research.

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I. INTRODUCTION

A. BACKGROUND

The process of assigning tasks requiring Tomahawk Land Attack Missiles (TLAMs) to firing units (e.g., specific ships in a fleet) is called *predesignation*. Predesignation is performed in two phases. Phase 1 is conducted at the fleet level, where the Tomahawk Strike Coordinator (TSC) allocates tasks to available firing units. Phase 2 refines the allocation on each individual firing unit given the allocations in Phase 1 [Hodge, 1999].

The Tomahawk missile is launched from a surface ship or submarine in support of an attack against a target during a *strike*, using information contained in the corresponding *mission*. A *task* is a mission with the associated period of time during which the mission is to be accomplished, and is sub-divided into *task parts*. A *primary* task part is fired to accomplish the task. A *ready-spare* or *backup* task part is fired if the primary missile fails to launch and is assigned, respectively, to the same firing unit, or a firing unit other than that to which the primary task part is assigned [Arnold, 2000]. We assume that the primary task part is launched, and that the ready-spare and back-up task parts are not.

Currently, there are two Tomahawk missile variants, Block II and Block III. A Block II missile is less capable (e.g., it has less range) than a Block III missile. There are two warhead configurations for a Block II and Block III Tomahawk missile; either the missile possesses a conventional unitary warhead (C), or the missile possesses a submunition dispenser for the payload (D). The next generation of Tomahawk missiles, the Block IV Tactical Tomahawk missile, will have improved avionics and performance [Navy Fact File, 2002].

Each task requires a specific type of missile. For example, a task whose objective is the destruction of an enemy command bunker requires a different kind of Tomahawk missile

warhead than a task whose objective is the destruction of an enemy integrated air defense radar site. However, some tasks can be accomplished with either a Block II or a Block III missile, in which case the TSC allocates the task to the less capable Block II missile, if possible, in order to preserve strike capability and flexibility for future missions. The extent to which future strike capability is available is measured as *follow-on strike capability* or *residual firepower*.

Tomahawk missiles are usually launched from surface ships via the *Vertical Launch System* (VLS). Using this system, missiles are stored in *half-modules*. A half-module consists of four cells, each of which contains a single Tomahawk missile. When preparing for launch, only one missile in each half-module may be powered up and aligned at one time. This limitation is known as the *half-module constraint*. Two tasks *conflict*, i.e., cannot be assigned to the same half-module on the same surface ship, if their corresponding missiles must be launched within the time required for the VLS fire control system to "reset" itself. We nominally specify this amount of time between launches as 45 minutes.

Presently, the only submarine firing units that can launch Tomahawk missiles are the nuclear-powered attack submarines (SSNs). An SSN can store Tomahawk missiles in its torpedo room. These Tomahawk missiles are contained in canisters and loaded into torpedo tubes for horizontal launch. Tomahawks can also be launched from newer variants of SSNs via the Capsule Launch System (CLS), analogous to the VLS on surface ships. In this case, Tomahawks are stored vertically in capsules in the ballast tanks of an SSN and launched vertically from the capsules. The CLS does not have the half-module constraint of the VLS; therefore, each CLS can be thought of as a "single-shot half-module," or as a half-module with one cell, and Tomahawk missiles launched from SSNs via the CLS may be powered up and aligned at the

same time. The CLS that will be installed onboard the SSGN is similar to the CLS currently installed on the SSN.

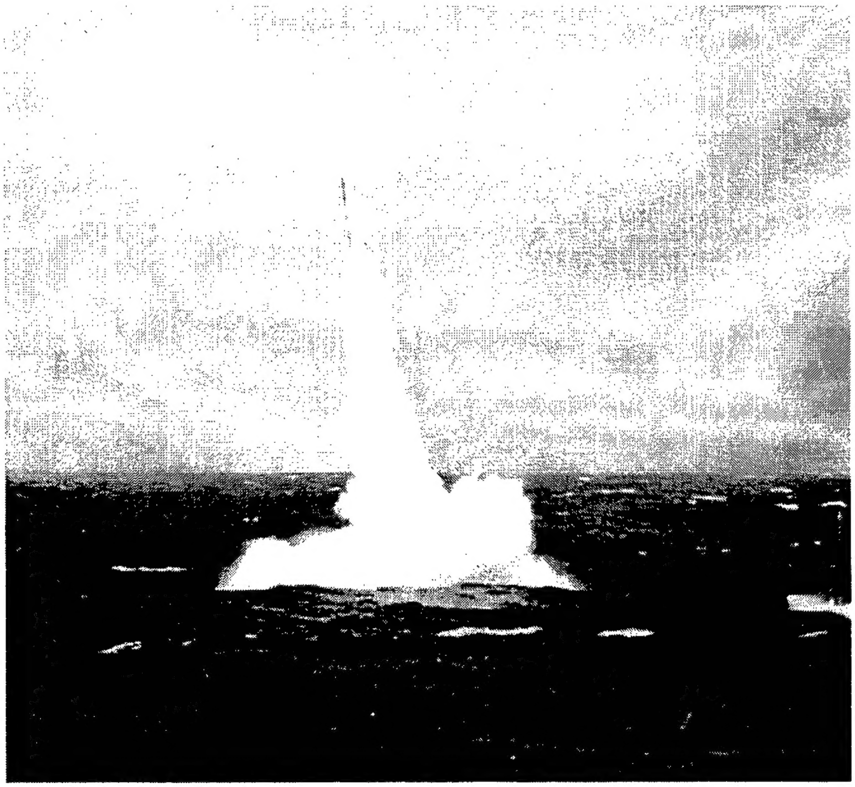

Figure 2 [Federation of American Scientists, 2002b]. An SSN launches a Tomahawk cruise missile. Note the periscope of the SSN on the right.

B. SUMMARY OF PAST WORK

Since 1998, with the help of Naval Surface Warfare Center, Dahlgren Division (NSWCDD), several theses at the Naval Postgraduate School have contributed to the development of a decision-support algorithm for Tomahawk predesignation.

LT Scott D. Kuykendall [1998], motivated by his fleet predesignation experience, first addresses Tomahawk predesignation in cooperation with NSWCDD. These motivational experiences are: (i) predesignation is currently done using paper and pencil, which is inefficient and error-prone, and (ii) currently-fielded predesignation software is not user-friendly and produces predesignations that can be trivially improved by inspection. Kuykendall uses an

integer program that considers single-firing unit or battle group follow-on strike capability to produce a non-trivial allocation scheme. This scheme yields better solutions than the manual predesignation scheme in a significantly shorter amount of time. Kuykendall considers both surface ships, and submarines that fire Tomahawk weapons from their torpedo tubes. Kirk [1999] proposes an optimization model for automatic surface ship predesignation at the fleet level. His mixed-integer linear program is based on the list of priorities, presented below in descending order of importance:

1. Make a complete allocation of tasks to firing units.
2. Minimize the use of firing units already occupied with other operations or not in geographical proximity to the strike.
3. Maximize the allocation of tasks to *expend* units, i.e., those firing units soon leaving the theater of operation.
4. Level the remaining tasks across *non-expend* firing units, i.e., those firing units remaining in theater.
5. Spread primary task parts across as many firing units as possible to prevent single-point failures among primary tasking.
6. Spread backup task parts across as many firing units as possible to prevent single-point failures among backup tasking.
7. Allow for the use of the least capable missile for each mission.
8. Maximize residual salvo capacity.

Kirk applies three solution methods to his model. First, he attempts to solve the model as a "single, monolithic problem." This approach, he discovers, is computationally impractical. Next, he approaches the problem using a hierarchical restriction method, which consists of solving the monolithic problem as a series of sub-problems, ordered with respect to the priority of each objective. This approach produces solutions of reasonable quality, but not in an operationally feasible amount of time. To reduce solution time, Kirk implements a simplified optimization-based heuristic, which produces solutions comparable to those of the hierarchical restriction method, but in significantly less time. Nonetheless, the solution time of the algorithm is still too long to be practical for implementation. Based on Kirk's work, Hodge [1999]

develops a non-optimization-based heuristic, which reduces solution times, though at the expense of solution quality.

Arnold's [2000] heuristic improves Hodge's not only by modifying the algorithm to improve solution quality, but also by providing the TSC a choice for the method of task allocation, i.e., automatic, partial, or manual allocation, thus giving the TSC more control over the predesignation process. The heuristic also ensures that a better solution cannot be achieved by a simple, one-complement interchange. Arnold's extension of the predesignation heuristic also includes SSNs as firing units. Because both the SSN and the SSGN are submarine firing units that use CLS capsules, Arnold's extension to include predesignation of CLS TLAMs on SSN firing units is most relevant to this technical report.

Kubu [2001] enhances the heuristic by providing functions that aid the TSC in determining—in the event of an incomplete strike allocation—why a task or tasks cannot be allocated, and prescribing modifications to enable a complete allocation of tasks. Wingeart [2001] validates the heuristic solutions with exercise data and demonstrates that the heuristic provides solutions superior to those of manual predesignation in fleet exercises.

C. THE SSGN FIRING UNIT

1. OHIO-Class Nuclear-Powered Ballistic Missile Submarine (SSBN)

Eighteen OHIO-class submarines, also known as Trident submarines, have entered naval service since the early 1980s. Each Trident submarine has 24 vertical missile tubes that are used to store two variants of Trident missiles. Trident C4 missiles are older and less capable than Trident D5 missiles. The first eight Trident submarines carry exclusively the older C4 missiles, while the remaining 10 Trident submarines carry exclusively the newer D5 missiles.

When the Nuclear Posture Review in 1993 reduced the number of Trident submarines from 18 to 14, the question arose as to what to do with the four oldest SSBNs, which still have over 20 years of service life remaining [Undersea Warfare, 2001]. The nuclear-powered guided cruise-missile submarine (SSGN) concept is a solution to the decision regarding the future of these submarines [Federation of American Scientists, 2002c]. Starting in FY 2002, Congress authorized funding "to begin the conversion of two Trident submarines into the SSGN (nuclear powered guided-missile submarine) configuration." The amount of funding allocated for this conversion preserves the option of converting two additional Trident submarines into SSGNs [Legislative Notice, 2001].

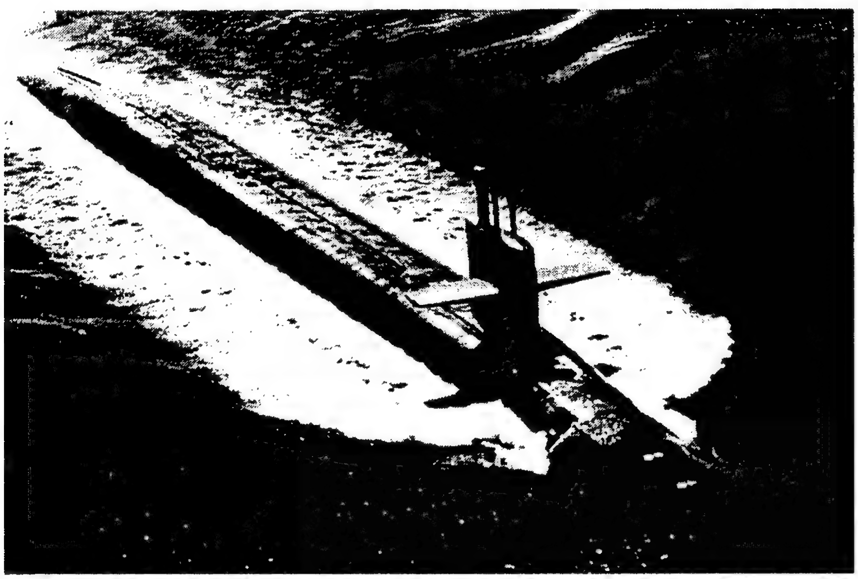

Figure 3 [Commander Submarine Group Nine, 2002]. The USS OHIO (SSBN 726) is the first of her class scheduled for conversion to SSGN in FY03.

2. Concepts of Operation for the SSGN

Tomahawk missiles onboard an SSGN will be stored in clusters of seven CLS capsules, the same as those used onboard CLS-equipped SSNs, inside at most 22 of the 24 missile tubes that had been used to store Trident missiles. Currently, there are three possible missile loadout

configurations for the SSGN, all of which correspond to missile inventories that far exceed the Tomahawk missile inventory of any extant Tomahawk firing units. In all three configurations, the first two missile tubes would be permanently modified with attachments for Special Operations Forces (SOFs) vehicles and also with lockin/lockout trunks for diver access to and from the submarine. In the Maximum Strike Configuration, the SSGN can be fully loaded with 154 Tomahawks in the remaining 22 missile tubes. The other two configurations are designed for a combination of TLAM strike and SOF missions. In these two configurations, SOF vehicles attached to the first two missile tubes obstruct the opening of the missile muzzle hatches of adjacent missile tubes underneath them. Hence, the corresponding obstructed missile tubes would then be used to stow various SOF equipment. For the configuration in which two missile tubes are blocked, the SSGN would be loaded with 140 TLAMs; if four tubes were blocked, 126 TLAMs would be loaded [Aronson, 1999]. Even though the SSGN has four torpedo tubes, to our knowledge, there are no plans to use the tubes for TLAM operations. The SSGN will use these torpedo tubes for undersea warfare.

The SSGN will share parts of the same missile launching system that the SSBN uses for launching Trident missiles. For example, the SSGN will store TLAMs in missile tubes that previously stored Trident missiles. Each missile tube has a missile muzzle hatch on top of the missile tube that is opened for missile launches from the tube. For a Trident missile, there is a fiberglass enclosure under each missile muzzle hatch that prevents the Trident missile inside the missile tube from exposure to seawater before launch. Unlike the Trident missile, however, the CLS capsule of a Tomahawk missile will have its own individual capsule enclosure. Each Trident missile also has its own ejection system that propels the missile out of the submarine; each CLS capsule will have its own individual ejection system. The Missile Compensation

System adjusts the ballast of the submarine in order to compensate for the additional weight of the seawater in the missile tube after the missile launch. This system will be used for the TLAM launches on the SSGN as well.

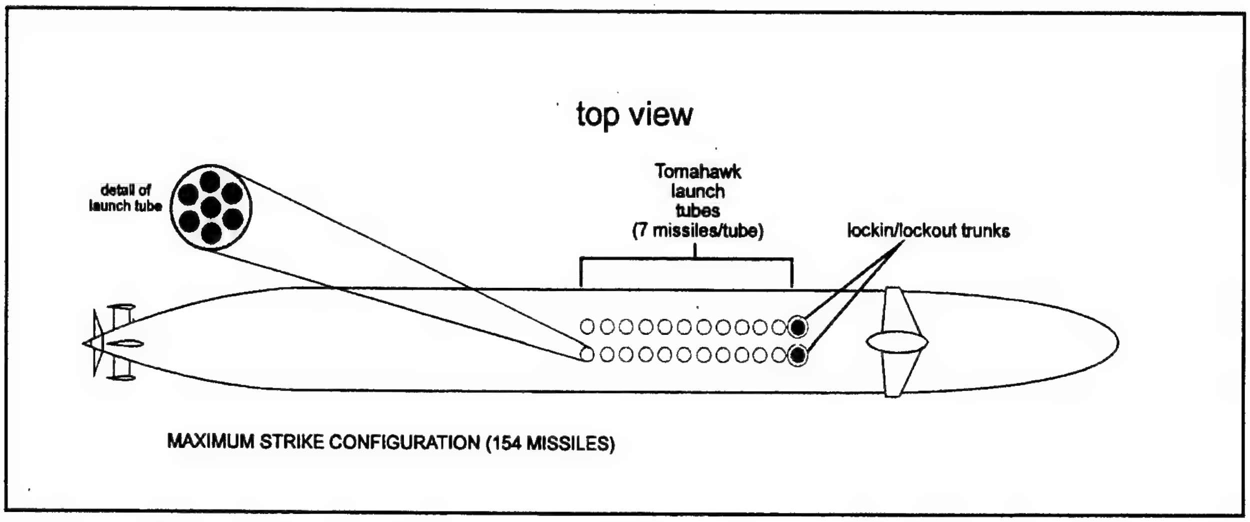

Figure 4 [Undersea Warfare, 2002]. In all three SSGN configurations, the first two missile tubes are permanently modified such that Special Operations Forces (SOFs) vehicles can be attached to the exterior of the submarine and accessed via the missile tubes. Each of the remaining twenty-two missile tubes contains a seven-pack of TLAMs arranged as shown in the magnified inset. In the Maximum Strike Configuration pictured above, the SSGN is fully loaded with 154 Tomahawk missiles in 22 of 24 missile tubes. The other two configurations have SOF vehicles that attach and dock on the back of the SSGN, rendering two or four additional missile tubes adjacent to the lockin/lockout trunks unavailable for TLAM launch. The former configuration would have 140 TLAMs loaded in the SSGN, the latter 126 TLAMs.

II. INCORPORATING THE SSGN IN THE PHASE 1 PREDESIGNATION HEURISTIC

A. POTENTIAL OPERATIONAL CONSTRAINTS

We developed a set of SSGN operational constraints following guidance from NSWCDD agents of SP-23, the SSGN Program Office (Table 1). We then presented these constraints to submarine officers and sailors during a site visit to Submarine Base Bangor, Washington, for critique and validation. The next two sections discuss the results of the site visit.

Table 1. List of Candidate Constraints.

Constraint	Description	Validated?
1. Number of Powered Up Missiles	A maximum of 32* missiles may be powered up concurrently.	Yes
2. Tube Hatch Open/Close Time	A minimum of 8* seconds is required to raise or lower an SSGN tube hatch.	Yes
3. Time Between Missile Launches	A minimum of 20* seconds is required between missile launches.	Yes
4. Number of Open Tubes	Only 6* SSGN tube hatches may be open at any time.	No
5. Starboard/Port Open Tube Imbalance	An imbalance of open missile muzzle hatches between port and starboard missile tubes should not be allowed to exceed 2*.	No
6. Forward/Aft Open Tube Imbalance	An imbalance of open missile muzzle hatches between forward and aft missile tubes should be minimized.	No
7. Marching Order	If possible, SSGN missile tubes should be opened in a specific order due to the fact that both a forward and an aft missile tube crew monitor the opening and closing of the SSGN tube hatches.	No
8. Total Number of Tubes Open	Minimize the number of SSGN missile tubes that would be opened to execute the total strike mission.	No

*An asterisk next to a number denotes that the values are subject to change.

B. SITE VISIT TO SUBMARINE BASE BANGOR

To better understand how SSGN missile operations can be incorporated into the TLAM predesignation heuristic, researchers from NSWCDD and an officer student at the Naval Postgraduate School visited Submarine Base Bangor, Washington, in April 2002. The team presented background, current work, and future work on the SSGN Tomahawk predesignation program to junior enlisted, junior officers, chiefs, department heads, and commanders. The discussion validated half of our operational constraints; the other half was considered operationally irrelevant.

The team also visited the USS MICHIGAN (SSBN 727) berthed at Delta Pier in Submarine Base Bangor. The MICHIGAN is designated for conversion to an SSGN. An Assistant Weapons Officer on the USS MICHIGAN guided our tour through the forward and missile compartments of the MICHIGAN, with particular emphasis on the Strategic Weapons System (SWS) and supporting systems. This was a unique opportunity for the team to appreciate the physical dimensions and layout of a candidate SSGN firing unit. Furthermore, this tour helped elucidate the revised list of operational constraints for the SSGN.

The project received full support and acceptance from submariners of all ranks who will be operating the SSGN. The success of tour also vindicated the paradigm shift to improve communications and cooperation between designers and operators in a major operational program. As a result of this site visit, the SSGN predesignation software will be more readily accepted by the operators and will better reflect operational considerations.

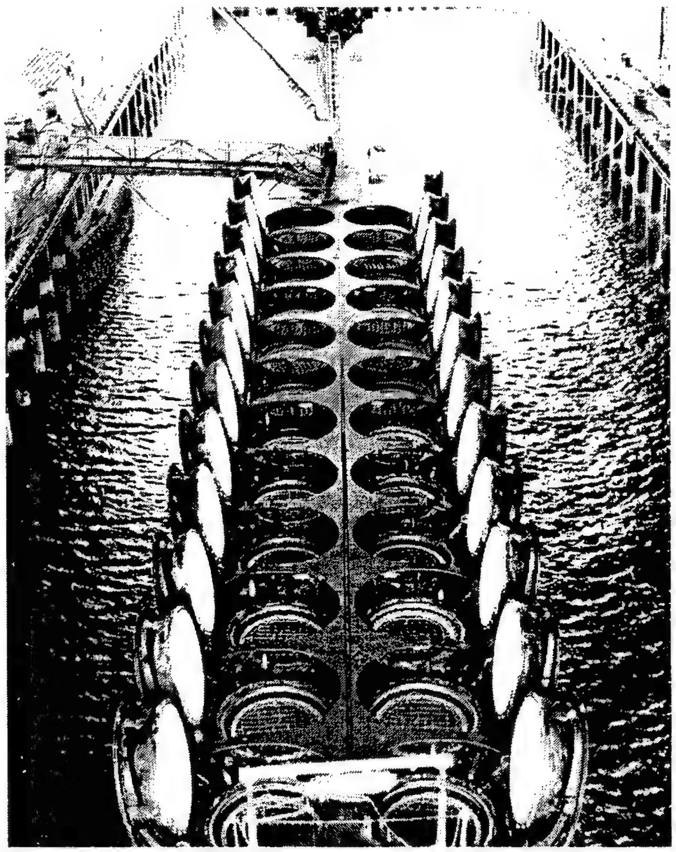

Figure 5 [DAQ, 2002]. The USS ALABAMA (SSBN 731) in the Explosive Handling Wharf (EHW) at Submarine Base Bangor with all of her missile muzzle hatches open.

C. VALIDATION OF OPERATIONAL CONSTRAINTS

Based on our site visit to Submarine Base Bangor, we present the results of our constraint validation with respect to Phase 1 predesignation below. Valid constraints are those that the submarine community deemed operationally necessary; invalid constraints were those the community deemed unnecessary.

1. Validated Constraints

Constraint 1: *Number of Powered Up Missiles.* The constraint on the maximum number of missiles that may be powered up concurrently is 32 missiles. This is a software restriction inherent to the fire control system, and is not limited to the SSGN. The heuristic, as designed for

SSNs, does not specify this constraint explicitly because it is implicitly considered by the fact that an SSN possesses only 12 CLS capsules and four torpedo tubes, allowing at most 16 missiles to be simultaneously powered up and aligned. Because the SSGN can carry 154 TLAMs, omitting a constraint to explicitly account for the fire control limitation may result in the heuristic suggesting the powering up and aligning of a number of missiles that greatly exceeds the fire control limit.

Constraint 2: *Tube Hatch Open and Close Time.* The timing for opening each missile muzzle hatch is set by an adjustable throttling valve that controls the flow of hydraulics to the hatch, and is a relevant operational restriction.

Constraint 3: *Time Between Missile Launches.* A time separation between missile launches is required to allow seawater to fill the empty canister after a missile is launched, and to allow any debris from the missile launch to drift clear of the missile tube so that it does not interfere with subsequent launches and missile muzzle hatch operations.

2. Invalid Constraints

Constraint 4: *Number of Open Tubes.* This constraint was allegedly based on limitations of the ship's service hydraulic plant. However, because the missile muzzle hatches are locked open during missile launch, the demand on the hydraulic plant is minimal, and, thus, all 24 missile muzzle hatches can be open simultaneously.

Constraint 5: *Starboard/Port Open Tube Imbalance.* This constraint was thought to minimize the impact of open missile tubes on the longitudinal stability of the SSGN. However, because a Tomahawk missile displaces significantly less volume than a Trident missile, the effect of a TLAM launch on the roll of the SSGN due to the difference in weight before and after

launch is insignificant. Even if all seven TLAMs were launched from the same missile tube, the difference in weight is still negligible compared to that of a Trident missile.

Constraint 6: *Forward/Aft Open Tube Imbalance.* This constraint was thought to consider the redundancy and reliability of the Ship's Service Hydraulic System during missile launch. The Ship's Service Hydraulic System has two headers (for redundancy) that circulate hydraulic fluid to hydraulic loads throughout the submarine, including the hydraulically operated missile muzzle hatches. One hydraulic header circulates hydraulics to the forward 12 missile tubes while the other header circulates hydraulics to the aft 12 missile tubes. Maintaining a balance of hydraulic loads between the two headers is preferred, in general, in order to prevent overloading any one header. However, because missile muzzle hatch operations are transient loads on the hydraulic system, they have minimal impact on the overall system reliability.

Constraint 7: *Marching Order.* The basis for this constraint was to minimize procedural changes, and hence operator retraining, from launching Trident missiles to launching Tomahawk missiles. During a Trident missile launch onboard an SSBN, two teams of missile technicians, each overseeing either the forward or aft missile tubes, position themselves around the missiles that are ready for launch. Because of the confined space in the submarine, separating the tube teams into fore and aft groups with a corresponding ideal "marching order" prevents the teams from interfering with each other while monitoring the missile launch. However, operating procedures other than subscribing to the traditional marching order can be developed to prevent tube teams from interfering with each other during a TLAM launch, and, in any case, operators would need minimal retraining to monitor a Tomahawk launch.

Constraint 8: *Total Number of Tubes Open.* This constraint was intended to allocate tasks to missiles in the same tube to minimize the amount of time that a missile tube spends

open. However, based on Constraints 2 and 3, the missile muzzle hatch may be closed after a TLAM launch and re-opened before the next launch from the same tube, which minimizes open tube time regardless of the tubes from which missiles are launched.

D. PROBLEM DEFINITION

1. Data Input

The subsequent paragraphs briefly describe the input data (Table 2) required by the heuristic. These data are also required for the SSGN, its inventory, and tasks that are allocated to the SSGN.

Table 2. Input Data Required for the Predesignation Heuristic.

Source of Data	Data Required
Firing Unit	1. Method of missile allocation
	2. Missile loadout data
	3. Current activities
	4. Geographical position
Task	5. Launch area
	6. Number and type of missile required
	7. Conflicts with other tasks
Weapon	8. Capability
	9. Value

Input 1: Currently, the heuristic permits three methods of missile allocation: (i) automatic allocation, i.e., the heuristic attempts to allocate all the tasks without user intervention, (ii) semi-automatic allocation, i.e., the user may allocate some tasks, and the heuristic completes the allocation, and (iii) manual allocation, i.e., the operator manually allocates all tasks without the use of the heuristic.

Input 2: Missile loadout data provide the heuristic information regarding the amount and types of Tomahawk missiles onboard the firing unit.

Input 3: A firing unit's current activities indicate the relative importance of engaging in a TLAM strike as opposed to remaining on its current function.

Input 4: A firing unit's geographic position determines whether the firing unit can launch one of its missiles in support of a strike.

Input 5: The area from which a Tomahawk missile must be launched to accomplish a task dictates which firing units are eligible to execute that task.

Input 6: The number and type of missile required for each task ensure that the firing unit to which the task is assigned has the requisite missiles to accomplish the task.

Input 7: The conflicts each task has with other tasks dictate which tasks can and cannot be assigned to missiles residing in the same half-module onboard the same firing unit.

Input 8: Each type of TLAM has a capability, and correspondingly, an inherent value depending on its variant and warhead type.

2. Constraints

We now review the relevance of the current predesignation constraints [Kirk, 1999] to the heuristic, given SSGN considerations. Some constraints, e.g., the half-module constraint, are obviously irrelevant to the SSGN. Others, e.g., accounting for the number of Tomahawk tasks that have been assigned to a firing unit, are independent of the SSGN. Of interest to us are SSGN-relevant constraints that may need to be modified to incorporate the new firing unit. The constraint numbering below corresponds to that in Kirk's thesis.

SALVO_{wfh} is a binary variable in Kirk's model that indicates whether or not, after a strike, any weapon of type w remains on firing unit f in half-module h. Constraint 16 states: "The variable SALVO_{wfh} is restricted to equal zero if all missiles in a half-module have been expended, for each firing [unit] and weapon type." This constraint remains unchanged for the

SSGN given the correspondence between a CLS capsule onboard an SSGN with a given missile type and a half-module on a surface ship having only one missile of a given type. That is, once the missile is launched from the SSGN, the CLS capsule is expended and the *SALVO* variable equals zero, as designed. Constraints 17 and 21 ensure that half-module constraints are accurately accounted for. Using the analogy that the SSGN contains "single-shot half-modules," these constraints need no further modification for the SSGN.

The following additional constraints are independent of firing unit type, or, in the last case, are irrelevant to the SSGN, and are not affected by the introduction of the SSGN:

- Constraint 2 counts the number of unallocated tasks.
- Constraints 3 and 4 require the firing unit to be in the same launch area as the primary and backup task parts, respectively.
- Constraint 5 ensures that a firing unit cannot launch missiles from more than one area.
- Constraint 6 accounts for the number of missiles selected from expend firing units.
- Constraints 7 through 10 count the number of missiles remaining on non-expend firing units after a strike.
- Constraints 11 and 12 assess the number of firing units that have been assigned primary task parts.
- Constraints 13 and 14 assess the number of firing units that have been assigned backup task parts.
- Constraint 15 accounts for the capability of the missile used vice what was necessary to use.
- Constraints 18 through 20 enforce the definitions of ready-spare and backup missile assignments.
- Constraint 22 ensures that only one missile may be selected for a task part.
- Constraint 23 ensures only one missile per set of conflicting tasks may be assigned to a half-module.

Therefore, based on our review of the constraints, we conclude that all of the above SSGN-relevant constraints remain unaffected by the incorporation of the SSGN into the predesignation heuristic.

3. Scoring Methods

Recall that Arnold [2000] enhances the predesignation heuristic by including submarines, *inter alia.* Hence, we now review the way in which Arnold incorporated SSNs, specifically, the way in which tasks are selected for predesignation to missiles onboard SSNs, to assess any differences in task assignment by using SSGNs for these predesignations.

Arnold's heuristic makes task allocations to firing units according to a set of hierarchical objectives and uses a *spread-ship scoring method.* This scoring method assigns different point values to each half-module, capsule, torpedo tube, and cell in order to quantify the value of each with respect to achieving the hierarchical goals [Arnold, 2000]. "Spread-ship scoring assigns two points to a firing unit for every half-module, CLS capsule, and torpedo tube that does not have a primary task part assigned to it, and it assigns one point for every cell, capsule, or torpedo tube that does not have an assigned primary task part" [Arnold, 2000]. These two separate point assignments are made to avoid conflicts between tasks (on surface ships) and to maintain residual firepower. Using the spread ship scoring method, the heuristic assigns the primary task part to the missile with the highest spread-ship score. Then, the heuristic assigns ready-spare and backup task parts to the same or another firing unit, respectively, with the next highest scores. Because the SSGN has significantly more capacity than any other firing unit, we examine whether this scoring method is appropriate for the SSGN.

To this end, we consider the following example. We compare a strike launched with two expend firing units, one of which is an SSGN and the other a Ticonderoga class cruiser. Suppose that the SSGN carries 154 TLAMs and the cruiser carries 32 TLAMs. Two conflicting tasks requiring the same missile type need to be assigned. Task 1 requires primary, ready-spare, and back-up task parts of, e.g., Block IIC, missiles. Task 2 requires primary and ready-spare task

parts only, also Block IIC. Based on spread-ship scoring, the SSGN receives a maximum possible 462 points (= 22 tubes × 7 CLS capsules per tube × 3 spread-ship points per capsule). The Ticonderoga receives a maximum possible 186 points (= 32 half-modules × 2 points per half-module + 122 cells × 1 point per cell). Hence, primary task parts are assigned to the SSGN, while back-up task parts are assigned to an "other firing unit," in this case, the Ticonderoga class cruiser. Now suppose the SSGN conducts subsequent TLAM strikes until 62 missiles remain onboard the SSGN, while the cruiser fires no (more) TLAMs. At this point, the SSGN's spread-ship score, 186, (= 62 capsules × 3 points per capsule) is equal to that of the cruiser's (assuming the redundant missiles of the first two tasks were not fired). Given additional conflicting tasks to be assigned in the same strike, either firing unit may now be selected for primary task part assignment. This allocation result agrees with the operational concept for which the SSGN is conceived—a submarine is capable of launching an overwhelming cruise missile strike, and the allocation method also serves the purpose of balancing TLAM inventories among firing units.

The heuristic defines the total penalty for a firing unit as the sum of its geographic and employment penalties. The heuristic uses a total penalty ratio to prioritize the order in which firing units are selected to receive tasks. The *firing unit-TLAM-penalty ratio*, ***R***, is the ratio of the total penalty of the firing unit divided by the number of TLAMs onboard the firing unit [Arnold, 2000]. If a task cannot be assigned to any firing unit with a zero ***R***-value, the heuristic considers firing units for task assignment in increasing order of their ***R***-values [Arnold, 2000]. Suppose we have an SSGN and a Ticonderoga-class cruiser that have equal total penalties; the SSGN has more TLAMs onboard than the Ticonderoga-class cruiser, and correspondingly, a smaller ***R***-value. Therefore, the heuristic would assign a task to an SSGN, rather than to the

cruiser, *ceteris paribus*. This selection is consistent with the concept of operation for the SSGN discussed directly above.

E. ALGORITHM SPECIFICATION

Salmeron [2002a, b, c] develops an algorithm specification based on prior TLAM predesignation thesis work. He proposes the use of an Entity Relationship Model to characterize the data structure of the heuristic algorithm (HA) and to identify various algorithm components as entities. For example, because the SSGN is a submarine firing unit in the HA, it is characterized by a Submarine entity in the Entity Relationship Model. Similarly, a task in the HA is represented by a Task entity in the Entity Relationship Model.

In addition to defining entities, the Entity Relationship Model also defines the proper relationships between the entities. There are two types of relationships between entities. The first type of relationship is the "one-to-many" relationship, i.e., an entity of one type may relate to one or more entities of another type. For example, for an SSGN with 154 TLAMs, a Submarine entity representing the SSGN relates to 154 Weapon entities. The second type of entity relationship is the "many-to-many" relationship, i.e., one or more entities of one type may relate to one or more entities of another type. For example, the relationships between tasks and task parts are represented by many-to-many relationships between Task entities and Part entities. In order to maintain consistency in the data and execution to the heuristic, many-to-many relationships in the data model are decomposed into two one-to-many relationships by using an intermediate entity. Hence, for example, the relationships between Weapon entities and Submarine entities are decomposed using Submarine-Weapons entities as intermediaries.

Salmeron organizes entity attributes in tables. Each entity data table has a table identifier, and the field descriptors in each table represent data input, output and other

calculations that are passed between entities [Salmeron, 2002a]. The entity attributes include user-defined parameters such as firing unit name, number and types of TLAMs onboard the firing unit, and the number of cells and torpedo tubes in which Tomahawk missiles are stored on the firing unit. Hence, for a Submarine entity representing an SSGN, the number of torpedo tubes designated for TLAMs is zero, and the number of capsules stored onboard can be specified as having a maximum value of 154. Similarly, in the Submarine-Weapon entity data table associated with the Submarine entity representing the SSGN, the attribute for the number of submarine weapons in the torpedo room is zero for the SSGN, and the attribute for the number of weapons of a single variant onboard the SSGN can be specified as having a maximum value of 154. We determine that these are the only entities in the data model affected by the incorporation of the SSGN.

Salmeron [2002b] arranges the processes in the HA hierarchically by levels. Superior processes in the HA call subordinate processes to perform calculations on attributes of entities in order to allocate task entities to firing unit entities. For example, the process for finding a firing unit to allocate primary and ready-spare task parts calls subordinate processes to find the TLAMs in half-modules, torpedo tubes, and CLS capsules onboard all firing units. Because the SSGN can be represented by the Submarine entity, the SSGN can be incorporated just like any other firing unit. Furthermore, its incorporation does not affect the structure and/or processes already established for other firing units, e.g., Ship entities, in the HA.

In summary, because the SSGN is similar to an SSN with all its TLAMs in CLS capsules, the SSGN can be incorporated into the HA without restructuring the existing code specifications.

III. CONCLUSIONS

This technical report examines the effect of incorporating the SSGN into the Tomahawk Phase 1 Predesignation heuristic algorithm. We evaluate SSGN-specific constraints based on feedback from submarine officers and sailors at Naval Submarine Base Bangor, Washington. Specifically, we determine that in order to correctly incorporate SSGNs, the algorithm must account for constraints on the maximum number of missiles that can concurrently be powered up, the minimum amount of time required to open and close a hatch from which a Tomahawk missile is fired, and the minimum amount of time required between missile launches. Additionally, we consider how to adjust the data structures and model of the existing TLAM allocation decision support algorithm to incorporate the SSGN, and find that only minor modifications are necessary. In summary, despite the SSGN's large TLAM inventory, the predesignation heuristic can incorporate the SSGN as a submarine firing unit, similar to how the heuristic considers the SSN, in a manner that is consistent with the goals of the heuristic.

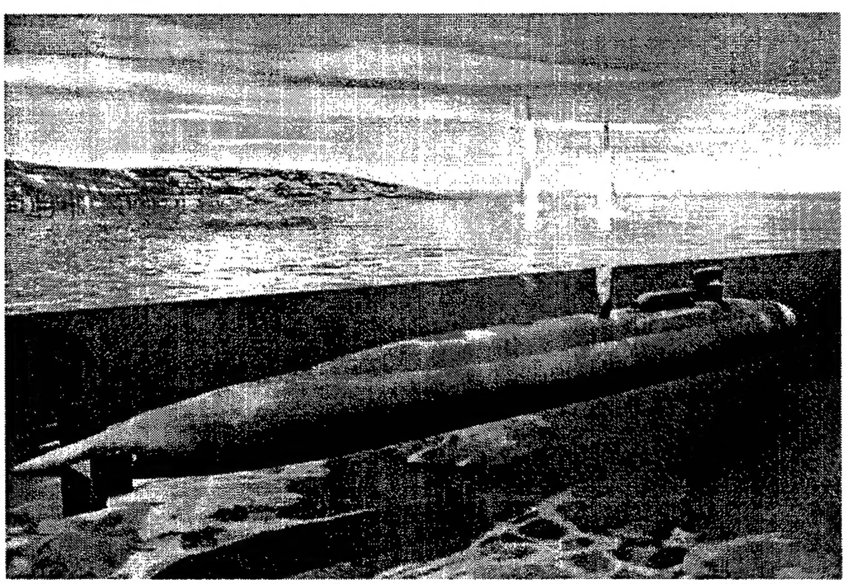

Figure 6 [Undersea Warfare, 2001]. Artist's rendering of an SSGN firing Tomahawk cruise missiles. Note the SOF vehicle attached to the SSGN just aft of the sail.

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